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Designing optimum locations and properties of MTMD systems

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Abstract

Reducing vibration of buildings during earthquake is of the primary concern to most structural engineers. Several methods have been proposed including the use of damper systems. This paper considers the optimization procedures of multi tuned mass damper (MTMD) systems. A number of researches have considered designing MTMD systems to reduce structural response during earthquake. However, most of the research considered only the properties of the MTMD, while the locations of MTMD are decided beforehand. This paper considers the optimization both the properties and location of MTMD in structures. The hybrid coded genetic algorithms (HCGAs) are used to optimize the dampers. The HCGAs are the optimization method that utilize binary coded GAs (BCGAs) and real coded GAs (RCGAs). The RCGAs are used to optimize the properties of MTMD, while the BCGAs are utilized to optimize the location of the dampers. Numerical examples are then carried out to see the ability of the proposed method in optimizing the locations and the properties of the dampers. Numerical examples are carried out to a three, ten-, and forty-story buildings. For the three- and ten-story buildings, the location of the MTMD is obtained at the top of the buildings, whereas for forty-story building the location of the dampers is depending on the mass ratio of the dampers. For 1% mass ratio, the locations of the dampers, are at the 39th and 40th floors, respectively. For 2% mass ratio, the dampers locations are obtained at the 38th and 40th floor, respectively; while for 4% mass ratio, the dampers locations are at 37th and 40th floors, respectively. Numerical simulations show the effectiveness of MTMD systems in reducing response of structures due to earthquake.

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Keywords: optimization; binary genetic algorithms; real coded genetic algorithms; hybrid genetic algorithms; multiple tuned mass dampers

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1. Introduction

A number of techniques have been introduced to control buildings against wind and earthquake loadings. It can be classified into four major classes: passive, active, semi-active, and hybrid control systems. Of the control systems, passive control is the most popular one due its simplicity. One type of passive control systems is tuned mass damper. It has been used in several buildings because of easy implementation. By adding a small mass, where the stiffness and damping are designed in a proper way, the vibration of building can be reduced. Nowadays multiple tuned mass dampers (MTMD) have been considered to control the motion of structures, where more than one TMDs are used [1-5]. Although the properties of MTMDs can be obtained by using available optimization methods, not many research has considered on how to place the MTMDs in structures. This paper considers the optimization of both properties and locations of MTMDs in structures.

2. Hybrid genetic algorithms

The optimization of damper properties and location of dampers is done by using hybrid genetic algorithms [6]. Hybrid coded genetic algorithms (HCGAs) are a combination of real coded genetic algorithms (RCGAs) and binary coded genetic algorithms (BCGAs), which is run simultaneously. In BCGAs, chromosomes are represented by number 0 and 1, and then are converted to integers or real numbers, whereas chromosomes in RCGAs are directly represented by real numbers. In this research, BCGAs are used to obtain the optimum location of MTMD and RCGAs are used to obtain the properties of MTMD. The GAs program developed in [1] are used in this paper. The binary and real coding are then combined following [6].

3. GA-H_2 norm, fitness function

Equation of motion containing passive device can be written as:

$$(\mathbf{M_o}+\mathbf{M_p})\ddot{\mathbf{X}}_\mathbf{s}+(\mathbf{C_o}+\mathbf{C_p})\dot{\mathbf{X}}_\mathbf{s}+(\mathbf{K_o}+\mathbf{K_p})\mathbf{X_s}=\mathbf{e_s}\,\ddot{x}_g \tag{1}$$

or

$$\mathbf{M_s}\ddot{\mathbf{X}}_\mathbf{s}+\mathbf{C_s}\dot{\mathbf{X}}_\mathbf{s}+\mathbf{K_s}\mathbf{X_s}=\mathbf{e_s}\,\ddot{x}_g \tag{2}$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ are mass, damping and stiffness matrices, respectively, $\mathbf{X}$ is displacement, $\mathbf{e_s}$ is the influence vector of ground motion to structures, $\ddot{x}_g$ is the ground acceleration. The subscript **o** and **p** refer to original structures and passive device, respectively. The equations of motion can be transformed into state space equation [1] as:

$$\dot{\mathbf{Z}}=\mathbf{AZ}+\mathbf{E}w \tag{3}$$

where,

$$\mathbf{Z}=\begin{Bmatrix}\dot{\mathbf{X}}_\mathbf{s}\\ \ddot{\mathbf{X}}_\mathbf{s}\end{Bmatrix},\quad \mathbf{A}=\begin{bmatrix}\mathbf{0} & \mathbf{I}\\ -\mathbf{M_s}^{-1}\mathbf{K_s} & -\mathbf{M_s}^{-1}\mathbf{C_s}\end{bmatrix},\quad \mathbf{E}=\begin{bmatrix}\mathbf{0}\\ \mathbf{M_s}^{-1}\mathbf{e_s}\end{bmatrix},\text{and}\quad w=\ddot{x}_g \tag{4}$$

where the output equation $\mathbf{z}$ can be obtained as:

$$\mathbf{z}=\mathbf{C_z Z} \tag{5}$$

in which $\mathbf{C_z}$ is the matrix that represent the output vector. It is to be noted that displacements, velocity, absolute acceleration, and their combinations may be included to the output vector $\mathbf{z}$. But in this research, the objective of the problem is to minimize displacement of the top floor. Because H_2 norm is used to obtain the optimum parameters, the problem can be cast into [1][7]:

$$\dot{\mathbf{Z}} = \mathbf{AZ} + \mathbf{E}w$$
$$\mathbf{z} = \mathbf{C_z Z}$$
$$\text{Such that } J = [tr(\mathbf{C_z L_c C_z}^T)]^{1/2} \longrightarrow \text{minimum} \tag{6}$$
$$\mathbf{A}^T \mathbf{L_c} + \mathbf{L_c A}^T + \mathbf{EE}^T = 0$$

where J is performance index, *tr* stands for trace, and $\mathbf{L_c}$ is the controllability Grammians [7].

Genetic algorithms (GAs) [8][9] are used to obtain the optimum solution. Because in GAs solution, fitness is to be maximized, the performance index (J) is converted to the fitness function:

$$\text{fitness} = \frac{1}{J} \tag{7}$$

4. Case Studies

A4.1. Three-story building plane frame

A three-story plane building frame as shown in Fig. 1 is used as an example. The properties of the structures is taken from [3] as follows:

$$\mathbf{M_o} = \begin{bmatrix} 10 & 0 & 0 \\ 0 & 10 & 0 \\ 0 & 0 & 10 \end{bmatrix} \text{kg}, \quad \mathbf{K_o} = \begin{bmatrix} 2000 & -1000 & 0 \\ -1000 & 2000 & -1000 \\ 0 & -1000 & 1000 \end{bmatrix} \text{N/m}, \quad \mathbf{C_o} = \begin{bmatrix} 1.246 & 0.176 & 0.097 \\ 0.176 & 1.343 & 0.272 \\ 0.097 & 0.272 & 1.519 \end{bmatrix} \text{(N-s/m)}$$

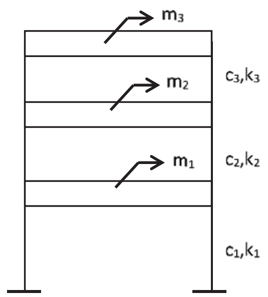

Fig. 1. Three-story building plane frame model

In [2] two dampers are utilized. First damper is located on the top floor and the second damper is at the second floor, where the mass of dampers is 0.5 kg and 0.075 kg, respectively. Properties of the damper obtained by [2] are c_{d1}=0.43 N-s/m, k_{d1}=9.11 N/m, c_{d2}=0.07 N-s/m, and k_{d2}=11.53 N/m. In this research, HCGAs are used for determining the properties and location of the dampers. BCGAs are used for determining the location of the first and second dampers, whereas RCGAs are used for obtaining the properties of the dampers. First, mass of each damper is determined beforehand. In this research, mass of the first damper is taken equal to the mass of the second damper = 0.2875 kg, which is about 2% of the total mass of building.

To obtain the location and the properties of the dampers, the program is run two times to see the consistency of the results. The optimization parameters used in this paper are as follows: number of population = 20, maximum generation = 2000, crossover rate = 0.75, and mutation rate = 0.1. The result of the optimum location of the first and second dampers is on the top floor (Table 1).The results are then compared to the results of [2] and [1].

Table 1 shows result of properties of dampers compared to [2] and [1]. For the validation, the result of case C in [1] is taken. This is because on case C in [1], the first and second dampers set in top floor. In [1] only optimum properties of the dampers are calculated. In the present approach, the locations and properties of dampers are simultaneously optimized using HCGAs.

Table 1. Comparison with others result research

Component	Research					
	Rana dan Soong (1998)		Arfiadi (2000) Case C		Present Result	
	Damper's Properties	Damper's Location	Damper's Properties	Damper's Location	Damper's Properties	Damper's Location
m_{d1} (kg)	0.5	Third Floor	0.2875	Third Floor	0.2875	Third Floor
k_{d1} (N/m)	9.11		4.6399		4.6496	
c_{d1} (N-s/m)	0.43		0.1231		0.1242	
m_{d2} (kg)	0.075	Second Floor	0.2875	Third Floor	0.2875	Third Floor
k_{d2} (N/m)	11.53		5.94		5.9318	
c_{d2} (N-s/m)	0.07		0.1487		0.1539	
RMS (cm)	5.09		4.98		4.97	
Peak (cm)	13.34		13.79		13.77	

4.2. Ten-story building

The second application is the use of MTMDs for a ten-story building. The properties of the structure is taken from [6], where in [6] the location and properties of single tuned mass damper is optimized using HCGAs. In this paper, multiple (two) tuned mass dampers are used, where the mass of each damper is taken = 57.5 t. This mass is half of the total mass of tuned mass damper used in [6]; or approximately 2% of the total mass of the building.

GAs program is run four times with different lower and upper bounds for predicting optimum values in order to ensure that same result is obtained. The optimization parameters are taken as follows: number of population = 15, maximum generation = 2000, crossover rate = 0.75, and mutation rate = 0.1. H_2 norm is taken as the objective function to obtain optimum location and optimum properties of multiple tuned mass dampers.

The resulting properties are then used to compare the response of the structure in [6]. It can be seen that the maximum displacement is quite similar as indicated in Fig. 2.

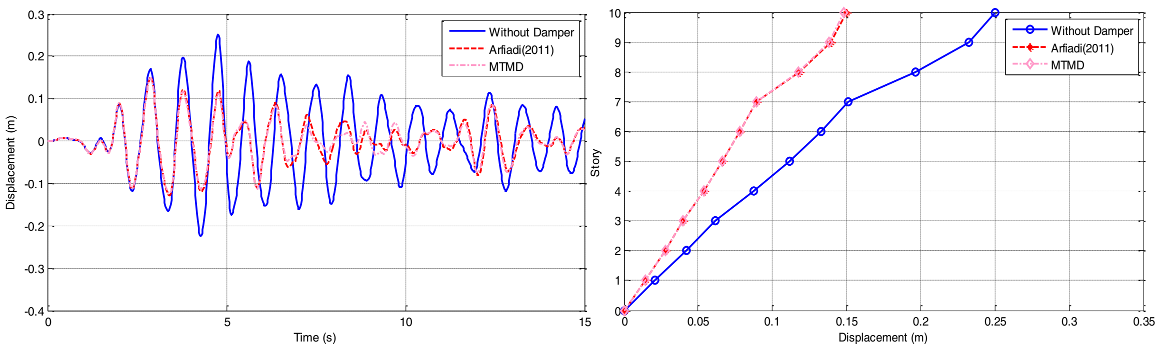

Fig.2. (a) Response of structure subjected to El-centro 1940 ; (b) Maximum displacement of each story

Maximum peak displacement in [6] is 4.96 cm , while in the present result is 4.74 cm. The resulting RMS top floor displacements are respectively 14.99 cm and 14.83 cm for Arfiadi and Hadi [6] and present result.

4.3. Forty-story building

The third application considered in this paper is a forty-story building with the property of the structure is similar as in example 2. The mass and stiffness for the eleventh-floor above is 489.3 ton and 367187.5 kN/m, respectively, which are the same as the mass and stiffness of top floor in example 2. There are three cases considered in this problem, i.e. case A: 1% mass ratio (202 ton), case B: 2% mass ratio (404 ton), and case C: 4% mass ratio (808 ton). The results of optimization is provided in Table 2. Table 2 shows that the first damper location is always on the top floor, while the second damper location is depend on the mass ratio. The location of second damper is on the 39th, 38th, and 37th floor, respectively for 1%, 2% and 4% mass ratio. In this case increasing the mass ratio resulting in decreasing the location of second damper.

Table 2. Properties of first and second damper for each mass ratio

Damper-	Damper properties	Case		
		A (m_d=1%.m_s)	B (m_d=2%.m_s)	C (m_d=4%.m_s)
1	k_{d1} (kN-m)	118.786	215.0841	355.4088
	c_{d1} (kN-s/m)	10.2226	26.7211	70.957
	Location	40	40	40
2	k_{d2} (kN-m)	149.9497	295.3134	552.3873
	c_{d2} (kN-s/m)	12.1104	34.2742	94.956
	Location	39	38	37

For comparisons, tuned mass damper is applied for all three mass ratio cases (1%, 2%, and 4%) and the properties and location for tuned mass damper is shown in Table 3, whereas Table 4 shows top floor peak displacement and root mean square displacement, respectively. Table 4 shows that top floor root mean square and peak displacement using tuned mass damper are quite similar to the one of MTMD. However, the natural frequency of structure using multiple tuned mass dampers is lower than the one using tuned mass damper as shown in Table 5.

Table 3. Properties and location of tuned mass damper

Damper	Damper Properties	Case		
		A (m_d=1%.m_s)	B (m_d=2%.m_s)	C (m_d=4%.m_s)
	kd (kN-m)	265.3954	501.2886	883.6015
	cd (kN-s/m)	39.1854	99.9969	245.1805
	Location	40	39	38

Table 4. Maximum displacement of top floor using tuned mass damper and multiple tuned mass dampers

Multi Tuned Mass Dampers				
Displacement	1%	2%	4%	Without Damper
Peak (m)	0.2196	0.2167	0.2118	0.2369
RMS (m)	0.0926	0.0903	0.087	0.0965
Tuned Mass Damper				
Displacement	1%	2%	4%	Without Damper
Peak (m)	0.2193	0.2162	0.2111	0.2369
RMS (m)	0.0929	0.0907	0.0872	0.0965

Table 5. Natural frequency of structure, period of structure, and frequency of dampers

System	Case	ω_s^* (rad/sec) Undamped	ω_s^* (rad/sec) Damped	T_s (sec) Undamped	T_s (sec) Damped	ω_{d1} (rad/sec)	ω_{d2} (rad/sec)
Multi Tuned Mass Dampers	A (m_d=1%.m_s)	1.2052	1.0578	5.2134	8.9098	1.0845	1.2185
	B (m_d=2%.m_s)		0.9981		9.4427	1.0319	1.2091
	C (m_d=4%.m_s)		0.8803		10.7063	0.9379	1.1693
Tuned Mass Dampers	A (m_d=1%.m_s)		1.0853		8.684	1.1462	-
	B (m_d=2%.m_s)		1.0353		9.1034	1.1139	-
	C (m_d=4%.m_s)		0.9558		9.8606	1.0457	-

*first mode of structure

4.4. Forty-story with optimization of MTMD mass

In this forth application, design variables are not only properties of multiple tuned mass dampers (k_{d1}, k_{d2}, c_{d1}, c_{d2}, first damper location, and second damper location) but also the mass of multiple tuned mass dampers (m_{d1} and m_{d2}) with certain mass ratio (1%, 2%, and 4%). Similar to the previous example, GAs program is run four times for each mass ratio to show the consistency result. Optimization parameters are taken as follows: number of population= 15, maximum generation = 2000, crossover rate = 0.75, mutation rate = 0.8, insert new individual each generation= 1%. Table 6 shows properties, location, and mass of multiple tuned mass dampers for mass ratio 1%, 2%, and 4% respectively. By comparing with the previous result, the location of the second damper is the same as in the previous example. Similarly, the resulting performance index of the current result (mass optimization) is not significantly different with the previous results as shown in Table 7. The different in performance index is only ± 0,0001.

Table 6. Properties, location, and mass of multiple tuned mass dampers for each mass ratio

Damper properties	Mass ratio		
	$m_{d\ total}$ = 1% . $m_{structure}$	$m_{d\ total}$ = 2% . $m_{structure}$	$m_{d\ total}$ = 4% . $m_{structure}$
m_{d1} (ton)	92.4773	159.9977	384.815
m_{d2} (ton)	109.5227	244.0023	423.185
m_{dtotal} (ton)	202	404	808
k_{d1} (kN/m)	139.0004	239.096	536.1496
k_{d2} (kN/m)	130.1186	264.6264	374.4471
c_{d1} (kN-s/m)	10.8396	23.7805	85.3364
c_{d2} (kN-s/m)	11.6332	36.9129	69.8751
First damper location	39	38	37
Second damper location	40	40	40
Fitness value (1/$H_{2\ norm}$)	0.5728	0.6184	0.6702

Table 7. Properties, location optimization compared with result of properties, location, and mass optimization of MTMD

Mass ratio	Performance Index		Difference of Performance Index
	Properties and location optimization (Section 4.3)	Properties, location and mass optimization (Section 4.4)	
1 %	0.5727	0.5728	0.0001
2%	0.6183	0.6184	0.0001
4%	0.6702	0.6702	0

5. Conclusion

Optimum solution of MTMD systems has been discussed in this paper, where hybrid genetic algorithms are applied to obtain location and properties of the dampers. Binary coded genetic algorithms are used for searching the optimum location of each damper, while real coded genetic algorithms are used for finding the optimum properties of MTMD and mass of each dampers. There are three difference mass ratio which are used in this paper, i.e. 1%, 2%, and 4%, respectively. For 1% mass ratio, the first damper is placed on the 39^{th} floor and the second damper location is on the top floor. For 2% mass ratio, the first damper is located on the 38^{th} floor when the second damper is on the top floor. For 4% mass ratio, the first and the second dampers are on the 37^{th} floor and top floor, respectively. In the last example the mass of each TMD in MTMD system is also optimized. From this example, the resulting objective function is similar to the previous result.

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